City ecosystem resilience analysis in case of disasters

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One of the tasks of urban and hazard planning is to mitigate the damages and minimize the costs of the recovery process after catastrophic events. The rapidity and the efficiency of the recovery process are referred to as resilience. A mathematical definition of resilience of an urban community has not yet been identified. In this paper we propose and test a methodology for the assessment of urban resilience to a catastrophic event. The idea is to merge the concepts of engineering resilience and ecosystem resilience. As first step we model a urban community by means of different hybrid complex networks, composed by human elements, i.e. the citizens, and physical elements, i.e. urban lifelines and infrastructures. As second step, we define a class of efficiency indexes on these hybrid networks. Then, we quantify the resilience of a urban system by computing these efficiency indexes before a simulated catastrophic event, after the event has occurred and during the subsequent recovery process. As a case study, we test this idea in case of simulated earthquakes in the city of Acerra, Italy.

Keywords: resilience, hazard, street networks, complex networks

I. INTRODUCTION

Resilience of urban systems is a key issue for contemporary society. Natural and human-induced risks threaten contemporary cities more than ever, because of the increasing urban population. The intensity of natural extreme events is in many cases also exacerbating, because of climate change phenomena. Urban management needs to cope with this issue and to implement risk mitigation and resilience strengthening policies. The assessment of city resilience against natural and human-induced hazards represents an urgent challenge for scientific community. This has been already highlighted by Dalziell and McManus (2004), which pointed out the need to introduce appropriate metrics to quantify resilience.

However, a unique definition for urban resilience against extreme events is not available. So far, two philosophies have inspired the recent approaches assessment the resilience of urban systems against disasters: the vision and the ecosystem vision. According to the former, city resilience depends on the capability of all the physical components, to absorb an external shock and quickly return to the initial state (Rourke, 2007; Reed et al., 2007; Bruneau et al., 2003; Pimm, 1984; Opricovic and Tzeng, 2002). The engineering approach can be straightforwardly used to quantify resilience of single urban components/infrastructures, by quantifying their time-varying performance in the aftermath of the shock. In the ecosystem approach, instead, resilience is defined as the capability of the whole urban system to recover with the full functionalities that existed before the shock, even without returning to the initial state (Holling, 1973, 1986, 2001; Kovalenko and Sornette, 2012). This implies that the system may evolve in something slightly different, keeping its identity in a broader sense, as well described by the theory of complex systems (Bar-Yam, 2003).

Complex systems are often defined as systems consisting of many interacting units with the ability to generate a non-trivial, collective behaviour through the combination of simple mechanisms acting at a local scale. In such systems, the evolution of the whole is not readily predictable by observing the behaviour of its components. From this point of view, cities and urban systems are undoubtedly complex systems (Batty, 2005). They have evolved over the centuries from the bottom up before reaching the actual configuration, under the concurrent action of a spontaneous unsupervised process, which has continuously shaped the urban structure at a microscopic level, combined with more recent planning efforts, which have tried to force more efficient structures on top of a pre-existing urban backbone. In fact, a city can be thought as a system composed of at least three layers. The first one is the technological layer, which consists of the buildings, the services and the infrastructures that physically link them together. The second one is a ge-

ographical layer, which takes into account the fact that cities are embedded in a geometrical space and their development is affected by the surrounding environment. Finally, there is an human component, i.e. the social network of citizens that reside, move and work within the physical frame.

Apparently, the ecosystem approach is more suitable for urban systems. Nevertheless, the engineering approach is also extremely meaningful, since the engineering resilience holds in the capability to reach a new state that is not "worst" than the pre-shock one. Hence, metrics to quantify the pre-shock and post-shock performance of a city and to assess whether the pre-shock performances are recovered after the event are fundamental tools to analyse the resilience of a city in a quantitative way. In this article we propose a series of measures to estimate the pre-shock and post-shock performance of a city, as required by the engineering approach, which take into account the possibility that the urban system evolves in a different configuration, as allowed by the ecosystem approach. We have also used these measures to test and compare three different strategies of reconstruction.

II. A METHODOLOGY TO QUANTIFY CITY RESILIENCE

The methodology presented here aims at identifying a unique approach to quantify, from an engineering point of view, the resilience of a city. However, inspired by the ecosystem vision, it moves from the point that urban systems can have a resilient response to a shock, also attaining a new configuration of the physical systems, that is a new dynamic equilibrium stage. In other words, we believe that a city can be considered resilient although some of the infrastructures do not recover their full functionality after the shock and new infrastructures are built elsewhere to recover the performance of the whole urban system. Given this principle, a first issue is to identify a proxy of the global urban system performance, to be computed before and after the shock and during the recovery phase in order to quantify the capability of a city to recover its performance before the shock occurred. We move from the observation that the street network is one of the most important aspects of a city, since its structure is intimately connected with the reachability of services and facilities and therefore with the overall quality of life perceived by the citizens. Consequently, we consider the efficiency of the street network of a city, appropriately weighted to take into account local population density and the physical location of services and facilities, as a meaningful proxy of the efficiency of the city as a whole. We make use of some basic concepts and metrics of complex network theory in order to quantify this efficiency and to compare the efficiency of different configurations. Complex network theory has proven to be a robust theoretical framework to study the structure of networked systems and has been largely employed in the last decade for the characterization of a variety of phenomena occurring in systems composed by interconnected units, including many biological, technological and social networks (Strogatz, 2001; Newman, 2003; Boccaletti et al., 2006). Recently, the complex networks approach has also been successfully employed to quantify and model the structural aspects of spatial networks in general (Barthélemy, 2011) and of street networks in particular (Crucitti et al., 2006; Strano et al., 2012).

A. Networks of urban street patterns

The functioning of the infrastructures and services of a urban agglomerate heavily relies on the existence of an underlying street network, and their efficiency usually depends on the structural properties of the urban street network. A huge amount of literature in urban morphology indicates that roads are a fundamental driver in urban evolution (Marshall, 2006; Southworth and Ben-Joseph, 2003) and complex network theory has provided significant contributions to the quantitative characterisation of urban street patterns, as reviewed in Barthélemy (2011). More recent studies have also shown that road networks are important for the dynamical processes occurring on them and for the evolution of urban areas in general (Batty, 2005; Strano et al., 2012; Bettencourt et al., 2007; Balcan et al., 2009). Reliability of infrastructure networks prone to natural hazards is largely discussed in available literature (Pinto et al., 2006). Connectivity based methods (Li and He, 2002; Dueñas Osorio and Rojo, 2011) and flow based methods (Franchin and Cavalieri, 2013) have been proposed and discussed to assess the reliability of lifelines in damaged configuration. Generally, networks can conveniently be described by means of graphs consisting of a set of points $\mathcal{N}$, called nodes or vertices, and by a set $\mathcal{V}$ of edges connecting pairs of points. A graph with $N = |\mathcal{N}|$ nodes ($\mathcal{N} = \{n_1, n_2, n_3, \dots n_N\}$) and $K = |\mathcal{V}|$ edges ($\mathcal{V} = \{v_1, v_2, v_3, \dots v_k\}$) can be represented by giving its adjacency matrix, i.e. the $N \times N$ matrix whose entry a_{ij} is equal to 1 if there is an edge connecting node i and node j, while $a_{ij} = 0$ otherwise. It is also possible to assign a weight or a length l_{ij} to each edge linking nodes i and j in a graph, thus defining a weighted adjacency matrix $\{l_{ij}\}$.

Spatial networks are a special class of complex networks whose nodes are embedded in a space associated with a metric. Typical examples of spatial networks include electric power grids (Kinney et al., 2005) and transportation systems including rivers, trade routes and street networks (Crucitti et al., 2006; Strano et al., 2012; Pitts, 1965). In the case of street networks, each crossing is represented by a node while edges represent street

segments, so that two nodes are connected by an edge if the corresponding crossings are adjacent to the same segment of road. In the following we denote by $\mathbb{G}(\mathcal{N}, \mathcal{V})$ the graph representing the street pattern, where $\mathcal{N}$ is set of street crossings and $\mathcal{V}$ is the set of street segments. Street networks are naturally embedded in a two-dimensional Euclidean space, whose metric is the usual Euclidean distance, so that the lengths l_{ij} of the edges satisfy the triangular equality (Barthélemy, 2011).

In transportation and communication networks it is usually important to know how to move or send an information from a node i to another node j. An alternate sequence of nodes and edges that starts from i and ends in j is called a *walk* from i to j. If there exists a walk between node i and node j, we say that i and j are *connected*. A maximal set of nodes which are mutually connected to each other is called a *component* of the graph. If not all the pairs of nodes in the graph are connected, then the graph is composed by more than one *component*. Each walk is associated to a cost, that is the sum of the lengths of the edges involved in the walk. If each node of the walk is traversed only once, then the walk is called a *path*. The path from i to j havbning minimal length is called shortest path and itsa length is denoted by d_{ij}. If two nodes are not linked by any walk, then d_{ij} is set to ∞, and the two nodes are said to be *disconnected*.

A measure of the typical separation between nodes in the graph is the *characteristic path length* L, that is the mean value of the length of the shortest paths between all the possible pairs of nodes:

$$L = \frac{1}{N(N-1)} \sum_{i,j \in N, i \neq j} d_{ij}. \tag{1}$$

In general, the lower the characteristic path length, the better the communication between any pair of nodes chosen at random. Using the characteristic path length to measure the resilience of a city is possible but indeed not convenient, since L becomes infinite as soon as there exists at least one pair of disconnected nodes. However, the result of a shock event on a city, like an earthquake or a flood, is often a disconnected street network, which always has an infinite characteristic path length independently of the actual number of pairs of sites that remain disconnected after the event. The efficiency of information exchange over a network, proposed in reference (Latora and Marchiori, 2001), is a measure which allows to overcome the subtleties due to infinite characteristic path lengths and can be therefore used to quantify the average reachability of the nodes of a network after a shock event. The efficiency e_{ij} of the communication between nodes i and j in a generic graph is defined as the inverse of the length of the shortest path connecting i to j, i.e. $e_{ij} = 1/d_{ij}$. The efficiency is minimal when i and j are disconnected, i.e. when $d_{ij} = \infty$. In the case of spatial graphs, it is possible and convenient to normalize the efficiency of a pair of nodes by the Euclidean distance between them, defining $e_{ij} = d_{ij}^{eucl}/d_{ij}$, so that the resulting normalized efficiency is maximal and equal to 1 if and only if the shortest path between i and j runs exactly along the direction of the geodesic which connects them. The *global efficiency* of a spatial network is defined as the average of the normalized pairwise efficiency over all possible pairs of nodes (Vragović et al., 2005):

$$E = \frac{1}{N(N-1)} \sum_{i,j \in N, i \neq j} \frac{d_{ij}^{eucl}}{d_{ij}}. \tag{2}$$

Notice that the global efficiency is normalized in $[0, 1]$, since in general the distance d_{ij} between node i and node j, which is measured as the total length to be traversed in order to get from i to j using a sequence of street segments, is larger than the Euclidean distance between i and j, so that each term in the summation is ≤ 1. Consequently, it is possible to compare in a consistent way the efficiencies of two distinct graphs G and G', even if they have a different number of nodes and edges.

B. Hybrid social-physical networks, HSPNs

The main idea behind the proposed methodology is to define Hybrid Social-Physical Networks (HSPN), and to assess their efficiency, before, during and after an extreme event. Basically, HSPN are physical spatial networks, composed by infrastructures and facilities, enriched and enlarged with further nodes, representing the citizens, and with further links, representing the interactions between citizens and physical components. One HSPN can be defined for each of the physical networks interacting with citizens. More specifically, one HSPN can be identified for each service provided by urban physical systems to citizens. For example, a HSPN can be defined for residences, namely the residential HSPN. In this case two sets of nodes and two set of links are identified:

- The set of intersection nodes, which we called $\mathcal{N}$.
- The set of building nodes, whose elements are the centroids of residential buildings (hereafter referred as $\mathcal{B}$).
- The set of street segments, which we called $\mathcal{V}$.
- The set of door links, whose elements represents the logical links connecting a building node to an intersection node, as showed in figure 1. This set is donoted by $\mathcal{V}_{\mathcal{B}}$

The street network augmented with the set of buildings and door links is denoted by $\mathbb{G}_{\mathcal{B}}(\mathcal{N} \cup \mathcal{B}, \mathcal{V} \cup \mathcal{V}_{\mathcal{B}})$. This network is enlarged with the social components to build the HSPN: each residential building is linked to further ending nodes, representing the citizens living in

FIG. 1: Network representation of a city. Buildings nested in the same point have null distance. The nodes representing these buildings belong to the set $\mathcal{I}$.

each building. The new links represent the interaction between citizens and buildings, that is the interaction between the social components and the physical components. This is clarified in Figure 1. The obtained network can be analysed in terms of different network performance metrics, defined in section II.C, to appreciate the capability of the urban system to provide services to citizens, that is, in this case, to allow citizens to live and interact with each other. Both the social and the physical part of the HSPN can be even more complex. For instance, if we consider the street network, toghether with residential and commercial buildings, we can estimate the capability of citizens to reach goods supplies. The resulting graph is denoted by $\mathbb{G}_{\mathcal{G}}(\mathcal{N} \cup \mathcal{B} \cup \mathcal{G}, \mathcal{V} \cup \mathcal{V}_{\mathcal{B}} \cup \mathcal{V}_{\mathcal{G}})$, where $\mathcal{G}$ is the set of nodes representing commercial buildings and $\mathcal{V}_{\mathcal{G}}$ is the set of logical links connecting this commercial buildings with the adjacents street segments. In graph $\mathbb{G}_{\mathcal{G}}$ the citizen nodes are attached to their corresponding building nodes, while goods nodes are connected to the commercial buildings where they are available. In the following we refer to this augmented network as to the goods HSPN. Similarly, a service HSPN can be built to assess the capability of citizens to be linked to schools, hospitals and other public infrastructures and to receive public services. In this case the underlying physical network is denoted by $\mathbb{G}_{\mathcal{S}}(\mathcal{N} \cup \mathcal{B} \cup \mathcal{S}, \mathcal{V} \cup \mathcal{V}_{\mathcal{B}} \cup \mathcal{V}_{\mathcal{S}})$, where $\mathcal{S}$ is the set of nodes representing public buildings and $\mathcal{V}_{\mathcal{S}}$ is the set of logical links connecting public buildings to intersection nodes.

Other lifelines can also be represented by means of appropriate HSPNs. For instance, the electric grid network and the water supply/sewerage network can be introduced, respectively, to investigate the capability of the urban system to provide citizens with electricity and water.

The potential of this approach lays in the fact that the global performance of the HSPN associated to a given service can be considered as a proxy of the accessibility of that service by the citizens, i.e. as a measure of the quality of the service provided. Thus, it is possible to quantify and compare the performance of the HSPN in distinct configurations of the physical networks, even if some infrastructures are not present in one of the configurations. By performing this analysis before and after the reconstruction which follows an hazardous event, which damage some of the pre-existent physical components of the urban system, we can quantify how the quality of public services provided to citizens has been affected, although the physical systems are rebuilt and rearranged in a new configuration. The idea is that this could represent an effective methodology to quantitatively assess the resilience (as suggested by the engineering resilience approach), but with a systemic perspective and focusing on the social components of cities (as indicated by the ecosystem resilience approach).

C. Measuring the performance of HSPNs

We define here some efficiency metrics for HSPNs which are inspired by the normalized global network efficiency given in equation (2). The mere definition (2) is inadequate to estimate the efficiency of the city, because it does not take into account the number of people living in each building. We can then devise a measure of efficiency of communications between people inside buildings by summing over all couples of inhabitants and using $d_{ij}^{eucl}/d_{ij} = 1$ for couples of inhabitants living at distance zero, i.e. assuming the maximum efficiency in their communications. Finally it is possible to calculate an expression of efficiency of communications of citizens, similarly to equation (2), as:

$$E_{cc} = \frac{1}{H_{tot}(H_{tot}-1)} \sum_{i \in \mathcal{B}} H_i \left((H_i - 1) + \sum_{j \in \mathcal{B}, j \neq i} H_j \frac{d_{ij}^{eucl}}{d_{ij}} \right), \tag{3}$$

where i, j are the indexes of nodes representing buildings, H_{tot} is the total number of inhabitants of the city, H_i is the number of people living in building i, $\mathcal{B}$ is the set of nodes representing buildings and d_{ij} is the length of the shortest path between i and j evaluated on graph $\mathbb{G}_{\mathcal{B}}$. Notice that in the summation over $j, j \neq i$ we assume that $d_{ij}^{eucl}/d_{ij} = 1$ for couples of buildings at zero distance (linked to the same street node). The term $(H_i - 1)$ inside the round brackets, times H_i, takes into account the couples of inhabitants that live in the same building and whose efficiency is $e_{ii} = 1$. We choose this measure to estimate the global efficiency of citizen-citizen communication in a city.

It is also possible to rewrite equation (3) in the following form, in order to avoid to impose $d_{ij}^{eucl}/d_{ij} = 1$ for

couples of buildings at distance zero:

$$E_{cc} = \frac{1}{H_{tot}(H_{tot}-1)} \sum_{i \in \mathcal{B}} H_i \left((h_i - 1) + \sum_{j \in (\mathcal{B} \setminus \mathcal{I})} H_j \frac{d_{ij}^{eucl}}{d_{ij}} \right), \tag{4}$$

where H_{tot} is the total number of inhabitants of the city, H_i is the number of people living in building i and h_i is the number of inhabitants that live in the set $\mathcal{I}$ of buildings with zero distance to building i; the summation over j is now limited to couples of nodes with non zero distance.

It is possible to write similar expressions also for goods HSPN by summing the outer summation over the set $\mathcal{G}$ of the buildings that contain goods, for instance shops, and normalizing by the total number of goods in the city G_{tot}, thus leading to equation:

$$\begin{aligned} E_{cg} &= \frac{1}{G_{tot} H_{tot}} \sum_{i \in \mathcal{G}} \sum_{j \in \mathcal{B}} G_i H_j \frac{d_{ij}^{eucl}}{d_{ij}} \\ &= \frac{1}{G_{tot} H_{tot}} \sum_{i \in \mathcal{G}} G_i \left(h_i + \sum_{j \in (\mathcal{B} \setminus \mathcal{I})} H_j \frac{d_{ij}^{eucl}}{d_{ij}} \right), \end{aligned} \tag{5}$$

where G_i is an estimate of the amount of goods in the shop $i \in \mathcal{G}$, d_{ij} is the length of the shortest path between i and j evaluated on the graph $\mathbb{G}_{\mathcal{G}}$.

Similarly, an estimate of the performance of citizens-schools HSPN is given by equation

$$\begin{aligned} E_{cs} &= \frac{1}{S_{tot} H_{tot}} \sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{B}} S_i H_j \frac{d_{ij}^{eucl}}{d_{ij}} \\ &= \frac{1}{S_{tot} H_{tot}} \sum_{i \in \mathcal{S}} S_i \left(h_i + \sum_{j \in (\mathcal{B} \setminus \mathcal{I})} H_j \frac{d_{ij}^{eucl}}{d_{ij}} \right), \end{aligned} \tag{6}$$

where S_i represents a measure of the importance of the school i (e.g. the floor area of the building or the number of students), $\mathcal{S}$ is the set of nodes representing school buildings and $S_{tot} = \sum_i S_i$. In this equation the length d_{ij} of a shortest path is evaluated on the graph $\mathbb{G}_{\mathcal{S}}$.

The main idea behind this approach is to use these measures as a proxy of the quality of the relationships between people and infrastructures; that is, in other words, through these measures one can appreciate how services of physical systems are available. Notice that, in the HSPNs efficiency quantification the importance of the final nodes of the physical network (i.e. the buildings) needs to be "weighted". To do this, the floor area was used; in fact, it can be interpreted as a proxy of the number of citizens living in each building, for the residential HSPN, of the amount of goods in each shop, for the goods HSPN, and of the importance of each school building, for the for citizens-schools HSPN.

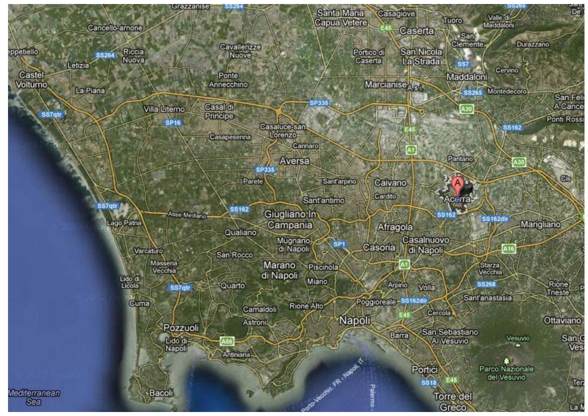


FIG. 2: Acerra location

FIG. 3: Acerra view

III. A CASE STUDY: THE CITY OF ACERRA

Acerra is a town in the Province of Naples, in Italy, about 20km north-east of Naples (Figure 2); it is one of the most ancient cities of the region, probably founded before 400 BC. The urban configuration, commonly experienced in medium cities in Italy, is composed by a dense historical centre, with mainly ancient masonry buildings, surrounded with more recent urban expansion areas, with mainly reinforced concrete buildings; the whole built-up area is surrounded by a countryside area, where a large industrial area is also located (Figure 3). The whole territory is extended over a surface of about 54km^2 and its population is estimated about 55000 inhabitants.

Acerra is prone both to seismic risk and flood risk. In particular, the seismic risk is generated by the seismogenetic areas located in the Appennines zones, at nearly one hundred kilometers; Figure 4 reports the seismic hazard in terms of annual rate of occurrence of events with Pick Ground Acceleration (PGA) larger than a certain value. Flood risk is due to the Regi Lagni river, bor-

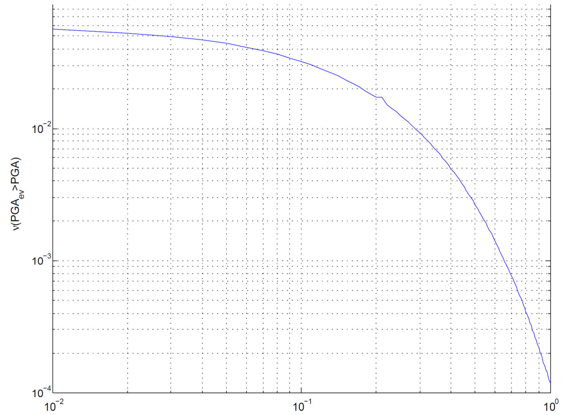


FIG. 4: Seismic hazard: annual rate of exceeding PGA vs PGA

dering the built-up area. Furthermore, an industrial risk can be also identified, because of the infrastructures and factories located in the industrial area.

A. Quantifying city resilience

The objective of this section is to practically deploy the proposed methodology, focusing on the seismic risk. The final aim is to quantify the aptitude of the city of Acerra to exhibit a resilient response, in case of earthquakes. To do this, the following steps have been implemented.

1. Data related to the buildings and the street patterns are collected by means of a GIS support. In particular, the buildings are divided into structural typologies and the total floor area is measured for each building. Data related to each street link is also collected. The network composed by street patterns and building is depicted in figure 5.

2. A fragility model is assigned to each building, given the structural typology; in other words, for each PGA value, the probability that the building overcome a specific damage state has been defined. In details, the “onset of damage” limit state has been considered, as the damage state making the building unfit for use, whatever is the use of the building. Furthermore, a damaged building can also interrupt the transit along the streets ahead. Thus, the probability that the building, once beyond the “onset of damage”, could make the street unfit for passage, was also introduced. It was made proportional to the ratio of the height of the building over the width of the street.

3. In each residential building, the number of residents is estimated. A similar estimation on the importance of the buildings is made for other non residential buildings. In example, for the commercial buildings and the school buildings, an estimation of the amount of goods and the number of students, respectively, is needed. Hence, different HSPN are built, joining physical networks, made by buildings and street patterns, and social networks made by residents, goods, students, etc.

4. Given the fragility model, different earthquake scenarios are generated, characterized by a certain value of PGA. In particular, in each scenario and for each building, the occurrence of a damage state beyond the “onset of damage” limit state is verified, by means of a Monte Carlo simulation, given the PGA value and the fragility model. Similarly, for the damaged buildings, the occurrence that the streets ahead are interrupted is verified by means of a Monte Carlo simulation, given, in this case, the probability that the street is made unpracticable. Then different recovery strategies are considered, each of them consisting of different urban configurations, where part of the damaged buildings and of the interrupted street patterns are progressively recovered, up to the reallocation of all the displaced citizens.

5. Finally, the generated HSPN are characterized by means of efficiency measures that are computed before and after the earthquake scenarios and after each reconstruction step of the considered recovery strategies.

B. Numerical analysis and results

We have implemented the aforementioned procedure for the city of Acerra in different earthquake scenarios, ranging between $0.05g$ and $1.0g$. We assume that the fragility models providing the probability of exceeding the “onset of damage” limit are characterized by a lognormal distribution function for both masonry and reinforced concrete buildings:

$$P_b\left(x;\mu,\sigma\right) = \frac{1}{2}\mathrm{erfc}\left(-\frac{\ln x - \mu}{\sigma\sqrt{(2)}}\right) \tag{7}$$

where erfc is the complementary error function and the variable x represents the value of PGA; the parameters μ, σ have been considered equal to $-1.03, 0.35$ for masonry buildings and $0.91, 0.29$ for reinforced concrete buildings, according to reference (Ahmad et al., 2011). Furthermore, it was supposed that a road in front of a damaged building is made impracticable with probability

$$P_r\left(h,l\right) = \begin{cases} 1 & \text{iff} \quad h \geq l, \\ \frac{h}{l} & \text{otherwise,} \end{cases}, \tag{8}$$

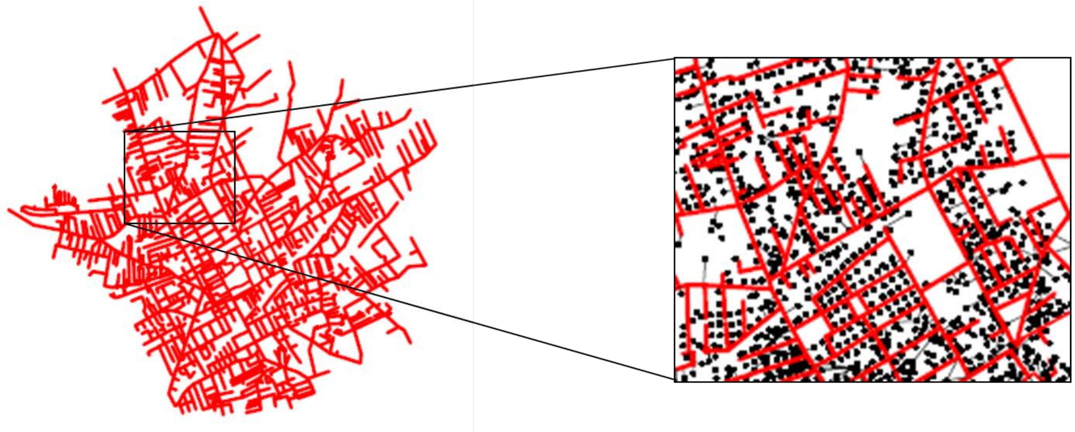


FIG. 5: Buildings (black points) and street patterns (red lines) network for the city of Acerra

where h is the height of the building and l is the width of the road. To estimate the number of residents in each building, one inhabitant per 30 square meters was assumed. This value was obtained by dividing the total number of inhabitants, i.e. 55000, by the total floor area of all the residential buildings. HSPN were built also for goods and students. In these cases, the floor area of commercial buildings and schools was used, respectively, as a proxy of the importance of each building. A set of measures have been carried out in the damaged configuration, after the considered earthquake scenarios and the values have been compared with those obtained in the undamaged configuration. In particular, three sets following measures have been computed:

1. The first set is composed by the efficiencies E_{cc}, E_{cs} and E_{cs}. The obtained values are normalized by the corresponding values in the undamaged configuration and are plotted vs. the PGA in figure 7;

2. A second set is composed by the following measures, whose values are reported in figure 6 vs. the PGA:

   - The number of undamaged buildings;
   - The number of not displaced citizens;

3. A third set of measures is performed on the network of street pattern $\mathbb{G}$ defined in section II.A. Let us recall that a street in front of a damaged building is feasible to be blocked. We simulate this process by removing the intersection nodes linked to a damaged building with probability P_r. The removal of such nodes implies also the removal of the incident links. The deletion of links could result in the fragmentation of the network in several components. This possibility could be disastrous, since it some parts of the city will remain isolated from the others. Then, it is possible to study how extreme events damage the street pattern measuring the following quantities:

   - The number of connected components;
   - The number S of intersection nodes belonging to the largest connected component;
   - The characteristic path length L of the largest connected component, as defined in eq. (1);

TABLE I: Absolute values in the undamaged configuration

E_{cc}	0.746
E_{cg}	0.252
E_{cs}	0.313
undamaged buildings	3493
not displaced citizens	55000
Number of connected components	1
Characteristic path length (m)	$L(0) = 599,2$
Nodes belonging to the largest component	$S(0) = 4638$

In the figures 7, 6 and 8 the values for the undamaged configuration are reported in correspondence of zero PGA. The absolute values are also reported in table I.

It can be observed from figures 6 that the number of undamaged building and the number of not displaced people have an exponential decay with the PGA with exponent $b \simeq -4$. We observe a faster exponential decay, with exponent $b \simeq -9$, for E_{cc}, E_{cg} and E_{cs} for values of PGA in the range between 0.25 and 0.6, as showed in figure 7. These results confirm that the efficiency of HSPNs can be reliably used as a proxies of the quality of an urban system.

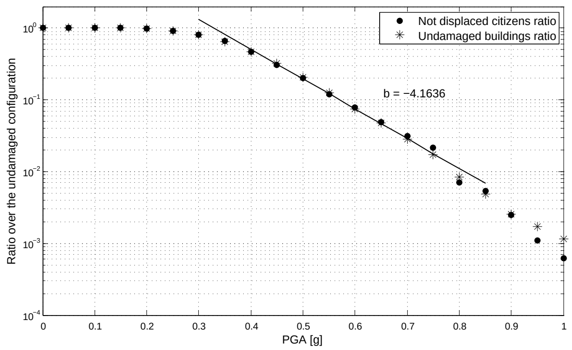


FIG. 6: Undamaged buildings and not displaced citizens vs PGA

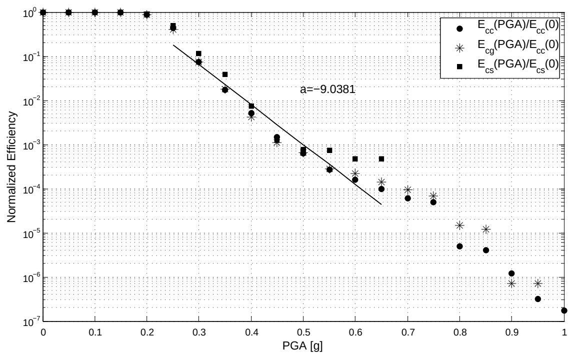


FIG. 7: Efficiencies E_{cc}, E_{cg} and E_{cs} vs PGA over the pre-shock values.

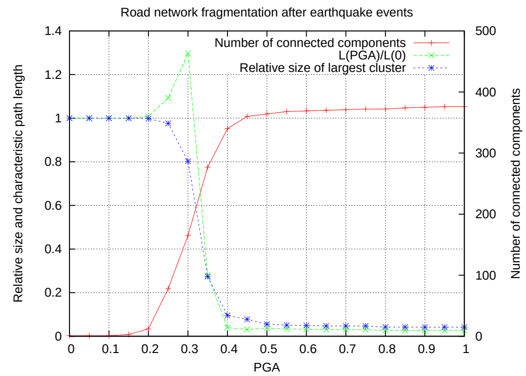
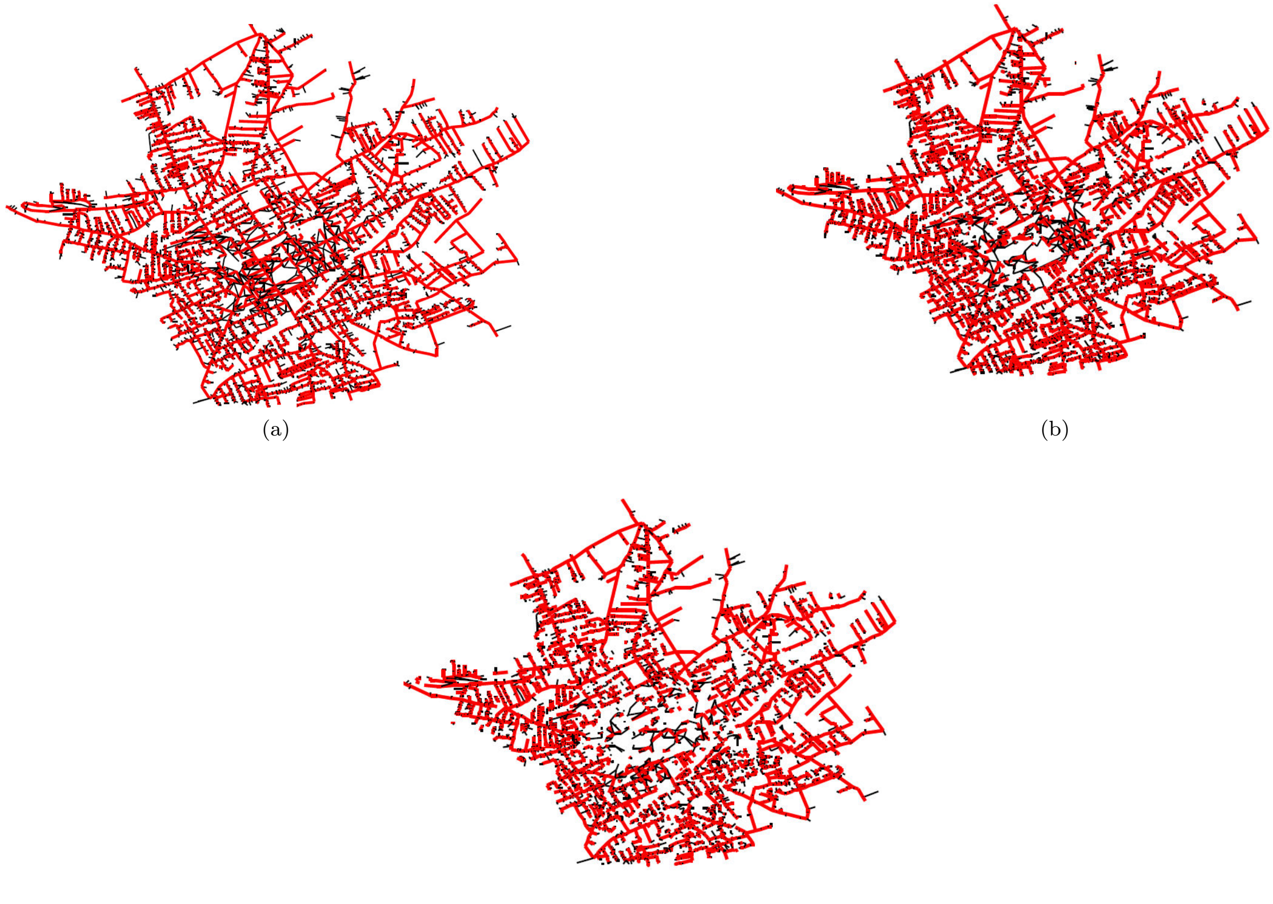


FIG. 8: Street network fragmentation under earthquake event. The number of connected components (red line), the normalized characteristic path length of the largest component $L(PGA)/L(0)$ (green line) and the normalized size of the largest component $S(PGA)/S(0)$ (red line), as function of increasing intensity of earthquake, measured in unit of PGA.

Furthermore, from figure 8 we note that behaviour of the street network is consistent with a percolation transition, indicating the existence of a critical range around $PGA = 0.3-0.4$ beyond which the street network is broken into many parts and loses the giant connected component (Stauffer and Aharony, 1994; Dorogovtsev et al., 2001). This is due to the adopted fragility functions that, in correspondence of this range of values, present a significant increase of the probability of collapse.

Reconstruction is analysed only for 3 earthquake scenarios, namely 0.2, 0.25 and 0.3 PGA. The configuration of the damaged physical network after each scenarios is reported in Figure 9. For each scenario, 4 reconstruction strategies are considered.

The first one, hereafter referred to as *status quo down-up*, consists in striving to return the city to the pre-event configuration. The process of reconstruction is discretized into n steps. In each step a fraction $1/n$ of the displaced citizens (those living in the damaged buildings) is allocated, assuming to rehabilitate the buildings from the smallest to the largest, i.e. from the cheapest to the most expensive. Blocked roads are recovered when the buildings that caused their interruption are reconstructed. In the second strategy, hereafter referred to as *status quo up-down*, as in the previous one, the city returns to the undamaged configuration, but the buildings are restored from the largest to the smallest. The third strategy, hereafter referred to as *new sites down-up*, consists of reallocating part of the displaced citizens in new residential sites. Also this process is discretized into steps. In the first step the new buildings are realized in 4 empty areas (highlighted in figure 10), to reallocate the 20% of the displaced citizens. Then the existing buildings are rehabilitated as in the first strategy, from the smallest to the largest ones, until all citizens have been reallocated. This strategy is often adopted in real cases to recover as soon as possible urban functionalities and has been experienced in several disaster recovery strategies, e.g. in the aftermath of the L'Aquila 2009 earthquake, in Italy, where the CASE project (Cosenza and Manfredi, 2010) was implemented. In this strategy some of the existing buildings are not recovered, since a part of the population is reallocated elsewhere. To re-establish the original urban street pattern, it has been assumed that the interrupted roads, that would have not been recovered (since interrupted by buildings that are not recovered), are re-established at the last step. The fourth strategy, hereafter referred to as *new sites up-down*, is



(a) (b) (c)

FIG. 9: Configuration of the damaged physical network after the $0.2PGA$(a), $0.25PGA$(b) and $0.3PGA$(c) earthquake scenarios.

similar to the previous one, but, after reallocating the 20% of the citizens in the new buildings, the existing buildings are restored form the largest to the smallest ones. The last two strategies, namely *status quo inwards* and *status quo outwards* consist of rebuilding the city as in its undamaged configuration, moving from the suburbs to the center of the city and viceversa, respectively. After each step of the reconstruction strategies the first set of measures are reiterated, so to appreciate how the efficiency of the HSPN is recovered when inhabitants are reallocated. The results are presented in Figures 11, 12 and 13.

In order to compare the several reconstruction processes it is possible to consider the areas under the recovery curve $Y(C) = E(C)/E_{pre-shock}$. In engineering the integration of the area under the curve that gives the recovery of the quality of an infrastructure as been labelled *resilience* R[1]:

$$R = \frac{\int_{t_1}^{t_2} Y(t)dt}{t_2 - t_1},$$

where t is the time in post-event days and t_1 and t_2 are the endpoints of the time interval under consideration (Reed et al., 2007). Instead of counting the time steps after the event, we measured the progress in terms of reallocated people C. The introduction of a further normalized function

$$y(C) = \frac{Y(C) - Y(0)}{1 - Y(0)},$$

which has value $y = 1$ for $Y(C) = 1$ and value $y = 0$ in the aftermath $Y(C) = Y(0)$, allows to compare the

[1] Some authors refer to the resilience as the area over the recovery function (Bruneau et al., 2003).

FIG. 10: Identification of the new residential areas (in black circle) in the *new sites* recovery strategy

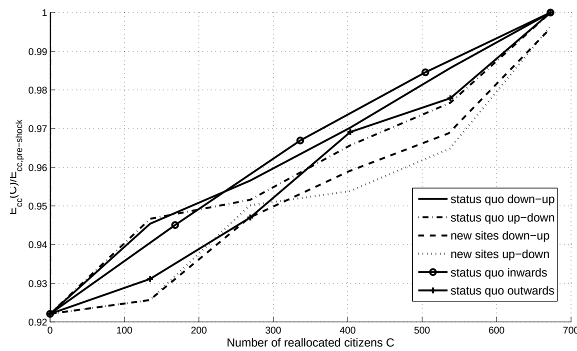
recovery processes which ensue after events of different magnitude. In formula:

$$\mathcal{R} = \frac{\int_0^{C_{max}} y(C)dC}{C_{max}}, \tag{9}$$

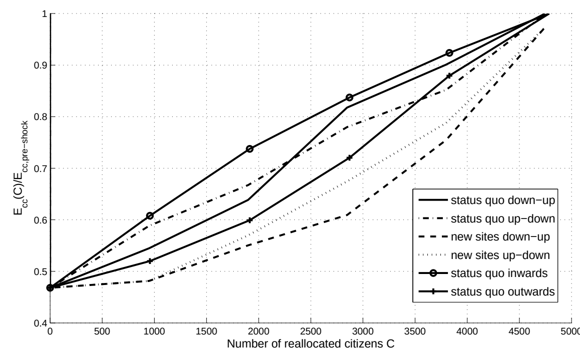
where C_{max} is the total number of people to be allocated after an earthquake of a given PGA. With this choice a resilience of $\mathcal{R} = 1$ corresponds to an instantaneous and total recover.

The values of resilience $\mathcal{R}$ are reported in table II. Observing the results in terms of recovered efficiency for the different strategies, a number of remarks can be made. First of all it can be observed that the *new sites* strategies provide with slower efficiency recovery, if compared with the *status quo* strategies. In particular, in the *new sites* strategies after the first step, consisting in the reallocation of the 20% of the inhabitants into new buildings, the efficiency values present a negligible increase. Furthermore, at the last step the efficiency values are not totally recovered to their initial values. This means that the new configuration of the city, with 4 new buildings used to reallocate the 20% of the displaced citizens, is less efficient than its original configuration. A further remark can be made with regards to the *up-down* and *down-up* options, corresponding to rehabilitating the buildings from the largest to the smallest and vice-versa, respectively. It can be observed that the most efficient option can not be unambiguously identified.

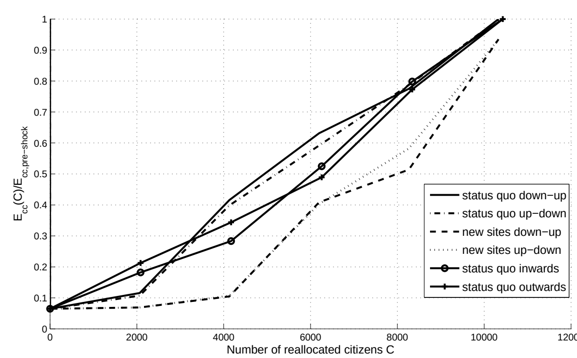
One more remark can be made with regards to the *status quo inwards* and *status quo outwards* strategies. We can observed that for earthquake of $PGA = 0.2$ and $PGA = 0.25$ the *status quo inwards* option is the most resilient/fastest strategy in recovering the efficiency E_{cc}, with respect to all the other strategies investigated. This result can be justified with the fact that, in the considered case study, the more vulnerable buildings, i.e. the masonry buildings, are in the centre of the city. Hence,



(a)

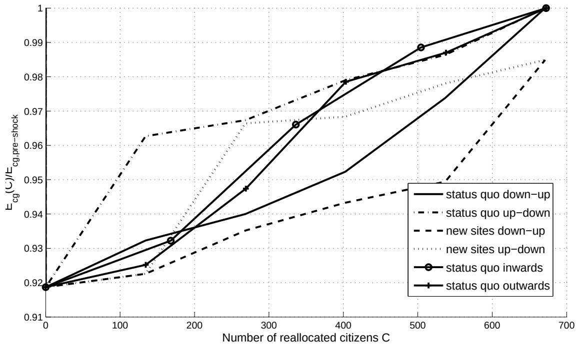


(b)

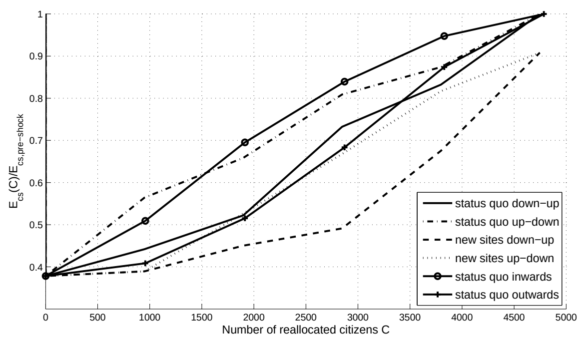


(c)

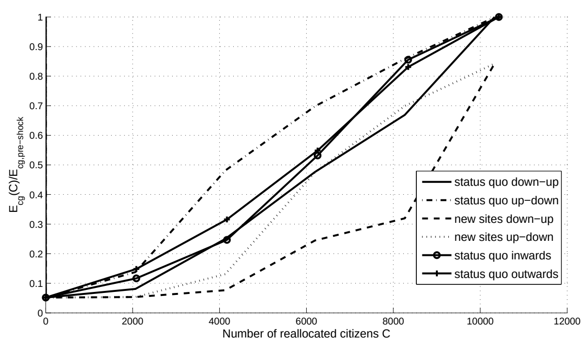
FIG. 11: Efficiencies E_{cc} for the 4 recovery strategies in the $0.2PGA$(a), $0.25PGA$(b) and $0.3PGA$(c) earthquake scenarios. The absolute values are normalized with the pre-shock efficiency $E_{cc,pre}$.



(a)



(b)



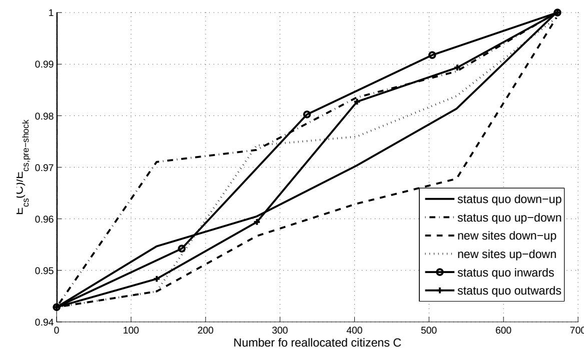
(c)

FIG. 12: Efficiencies E_{cg} for the 4 recovery strategies in the $0.2PGA$(a), $0.25PGA$(b) and $0.3PGA$(c) earthquake scenarios. The absolute values are normalized with the pre-shock efficiency $E_{cg,pre}$.

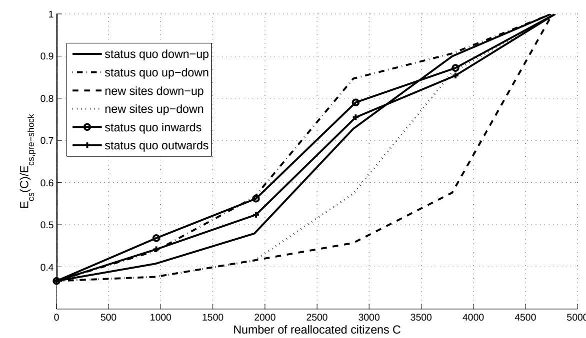
TABLE II: Resiliencies $\mathcal{R}$ of the different reconstruction processes, computed using definition 9. For each couple HSPN and PGA, the rows highlighted in green correspond to the most resilient reconstruction strategy, while the rows highlighted in red correspond to the two less resilient strategies.

HSPN	PGA(g)	reconstruction strategy	$\mathcal{R}$
cc	0.2	status quo outwards	0.45103
cc	0.2	status quo inwards	0.54305
cc	0.2	new sites up-down	0.36745
cc	0.2	new sites down-up	0.38167
cc	0.2	status quo up-down	0.49093
cc	0.2	status quo down-up	0.53522
cc	0.25	status quo outwards	0.41814
cc	0.25	status quo inwards	0.56392
cc	0.25	new sites up-down	0.33597
cc	0.25	new sites down-up	0.29166
cc	0.25	status quo up-down	0.48142
cc	0.25	status quo down-up	0.48695
cc	0.3	status quo outwards	0.43343
cc	0.3	status quo inwards	0.42705
cc	0.3	new sites up-down	0.28591
cc	0.3	new sites down-up	0.2719
cc	0.3	status quo up-down	0.44731
cc	0.3	status quo down-up	0.45894
cg	0.2	status quo outwards	0.50176
cg	0.2	status quo inwards	0.52697
cg	0.2	new sites up-down	0.47645
cg	0.2	new sites down-up	0.2676
cg	0.2	status quo up-down	0.64261
cg	0.2	status quo down-up	0.40413
cg	0.25	status quo outwards	0.41148
cg	0.25	status quo inwards	0.57556
cg	0.25	new sites up-down	0.37071
cg	0.25	new sites down-up	0.24389
cg	0.25	status quo up-down	0.54795
cg	0.25	status quo down-up	0.42674
cg	0.3	status quo outwards	0.4452
cg	0.3	status quo inwards	0.42564
cg	0.3	new sites up-down	0.32646
cg	0.3	new sites down-up	0.1863
cg	0.3	status quo up-down	0.51513
cg	0.3	status quo down-up	0.36771
cs	0.2	status quo outwards	0.47934
cs	0.2	status quo inwards	0.55227
cs	0.2	new sites up-down	0.47788
cs	0.2	new sites down-up	0.31461
cs	0.2	status quo up-down	0.60778
cs	0.2	status quo down-up	0.43367
cs	0.25	status quo outwards	0.44969
cs	0.25	status quo inwards	0.48693
cs	0.25	new sites up-down	0.33903
cs	0.25	new sites down-up	0.21212
cs	0.25	status quo up-down	0.50718
cs	0.25	status quo down-up	0.4307
cs	0.3	status quo outwards	0.51258
cs	0.3	status quo inwards	0.41402
cs	0.3	new sites up-down	0.27946
cs	0.3	new sites down-up	0.29614
cs	0.3	status quo up-down	0.43986
cs	0.3	status quo down-up	0.47104

in the post event configuration the center of the city is much more disconnected, looking like a “hole” in the HSPN networks (figure 9). Thus, in the *outwards* strategy the first steps are not so efficient since the building are restored onto a seriously damaged network. On the contrary, in the *inwards* strategy, the restored buildings are progressively reinstalled onto a network which is also progressively reconnected, making this strategy more resilient.



(a)



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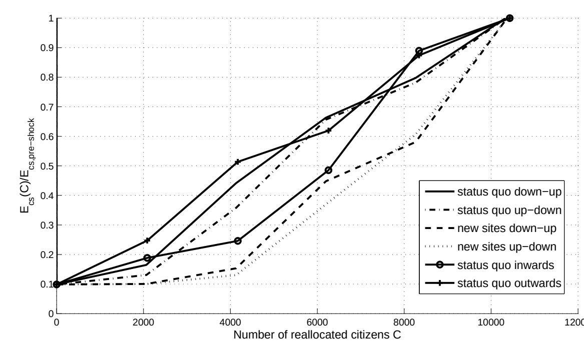

(c)

FIG. 13: Efficiencies E_{cs} for the 4 recovery strategies in the $0.2PGA$(a), $0.25PGA$(b) and $0.3PGA$(c) earthquake scenarios. The absolute values are normalized with the pre-shock efficiency $E_{cs,pre}$.

IV. CONCLUSIONS

In this paper we proposed a novel methodology to quantify the resilience of complex social-physical urban systems against disasters. This methodology aims to merge together the two classical approaches to resilience: the engineering resilience, generally meant as the capability of a system to recover its initial configuration after a shock, and the ecosystem resilience, generally meant as the capability of a system to recover its functionality after a shock, even in a new configuration of its components, different from the pre-shock one. The procedure presented here is inspired by the idea that city resilience should be assessed taking into account its social components, namely the citizens, which are the final users of the urban system as a whole. Our approach to quantify city resilience is based on the efficiency of hybrid networks composed by humans and urban infrastructures. In order to assess the capability of a city to recover its functionality after a shock event, we compare the efficiency of the corresponding hybrid networks before and after the shock event has occurred. We have discussed the results obtained on a case study, the city of Acerra, for which we simulated different earthquake scenarios and we analysed three hybrid networks, namely the networks providing residences, goods and schools. Different recovery strategies have been investigated, consisting in restoring the pre-event configuration or establishing a new configuration, with different reconstruction priorities.

While the main idea of the methodology presented here is to assess the resilience of urban recovery, the quantification of the efficiency of hybrid networks can be employed also for other purposes, e.g.:

1. To compare the efficiency of different urban configurations or different urban planning strategies. This would be a urban planning task;

2. To design the reconstruction operations after an hazardous event; the best reconstruction strategy can be selected, identifying the physical configuration which maximises the performances of all the hybrid networks.

It is underlined that, with regards to the assessment of post-event recovery strategies, the procedure here implemented does not account for the availability of financial resources. In fact, resilience is quantified in terms of reallocated citizens and not in terms of elapsed time after the event. Thus, introducing the financial availability the time to reallocate citizens could be evaluated, that is the time to restore the damaged buildings and infrastructures. However, the availability of financial resources can be considered a social-economic background input, not depending on the adopted recovery strategy.

Once the financial "weight" is introduced, the procedure could be enriched considering different rehabilitation costs for different buildings and infrastructures. As an example, it is estimated that the cost of rehabilitating masonry buildings in the historical centre, in Italy, given the damage state, is twice as much the cost of rebuilding reinforced concrete structures; and construction time is also significantly higher. This would affect the performance of the *outwards* strategies that, starting rehabilitating the historical centre, would be even less effective than the *inwards* strategies.

Currently, further research activities on this topic are ongoing. The intention of the authors is to enrich and calibrate the measures on hybrid networks, to achieve a set of quantifiable efficiency values, to be used as proxy measures of the quality of life of the inhabitants of the urban systems. The final aim is to build a reliable tool to assess the quality of life in urban environments, in order to have an engineering quantification of the city resilience, with an ecosystemic and social-centric perspective.

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